



Geochemical evidence for diversity of dust sources in the southwestern United States

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Abstract—Several potential dust sources, including generic sources of sparsely vegetated alluvium, playa deposits, and anthropogenic emissions, as well as the area around Owens Lake, California, affect the composition of modern dust in the southwestern United States. A comparison of geochemical analyses of modern and old (a few thousand years) dust with samples of potential local sources suggests that dusts reflect four primary sources: (1) alluvial sediments (represented by Hf, K, Rb, Zr, and rare-earth elements), (2) playas, most of which produce calcareous dust (Sr, associated with Ca), (3) the area of Owens (dry) Lake, a human-induced playa (As, Ba, Li, Pb, Sb, and Sr), and (4) anthropogenic and/or volcanic emissions (As, Cr, Ni, and Sb). A comparison of dust and source samples with previous analyses shows that Owens (dry) Lake and mining wastes from the adjacent Cerro Gordo mining district are the primary sources of As, Ba, Li, and Pb in dusts from Owens Valley. Decreases in dust contents of As, Ba, and Sb with distance from Owens Valley suggest that dust from southern Owens Valley is being transported at least 400 km to the east. Samples of old dust that accumulated before European settlement are distinctly lower in As, Ba, and Sb abundances relative to modern dust, likely due to modern transport of dust from Owens Valley. Thus, southern Owens Valley appears to be an important, geochemically distinct, point source for regional dust in the southwestern United States. Copyright © 2002 Elsevier Science Ltd

1. INTRODUCTION

The sources and transport pathways of dust play an important role in global climate and biogeochemical cycling, because dust transcends topographic and oceanic barriers. Dust from distant sources is a major component of soils in arid and humid areas (e.g., Yaalon and Ganor, 1973; Reheis et al., 1995). This dust provides nutrients needed for plant growth (Swap et al., 1992; Drees et al., 1993) and influences hydrology by altering soil texture. Inhalation of dust enriched in toxic metals such as antimony, arsenic, cadmium, and lead—the majority of which are considered anthropogenic (e.g., Galloway et al., 1982)—probably is even more deleterious than is silicate dust to health (Ross et al., 1993), and such dust when deposited may affect plants and soils. These important potential effects of dust emphasize the need to understand the specific sources of dust and how these sources may change with climate and human land use.

The majority of studies of airborne dust in the southwestern United States employed air-filtration techniques for collection in urbanized areas and national parks and focused on those dust components that represent anthropogenic pollution (e.g., Young et al., 1988; Pinnick et al., 1993; Malm et al., 1994). However, most of these studies measure advected dust rather than deposited dust, which is most likely to affect plants and soils (Yaalon and Ganor, 1973; Reheis et al., 1995). Intensive monitoring of dust emissions from the dry bed of Owens Lake in southeastern California (Fig. 1) has documented the volume and composition of dust from this important source (Cahill et al., 1996).

A regional network of dust traps installed in southern Nevada and California in 1984 collected dust samples, including

both wetfall and dryfall components; additional dust traps were installed in Owens Valley in 1991 to investigate dust from Owens (dry) Lake. In this report, we examine the contributions of different local sources to dust in the southwestern United States by comparing elemental analyses of samples collected from a subset of the dust traps to analyses of samples from potential source sediments, such as alluvial and playa deposits. Previous studies using the same sites showed that sparsely vegetated alluvial plains and fans are much larger sources of modern dust than are playas in most years (Reheis and Kihl, 1995), with the exception of the artificially desiccated Owens (dry) Lake (Reheis, 1997).

2. SAMPLING AND ANALYTICAL METHODS

2.1. Collection of Dust Samples

The dust-trap sites used in the present study comprise a subset of regional sites (Reheis and Kihl, 1995) and sites in Owens Valley (Reheis, 1997). In 1989 a dust trap was added at many of the regional sites to increase the amount of samples collected, and some sites were dismantled. The 37 regional sites that were retained were sampled about every 2 yr. The dust traps in Owens Valley were sampled twice a year from 1991 to 1999, in April or May and October or November.

The design of the dust traps is described in detail in Reheis and Kihl (1995). Briefly, the dust trap consists of a Teflon- or enamel-coated angel food cake pan mounted on a steel post ~2 m above the ground. This height nearly eliminates the trapping of coarse grains traveling by saltation (Chen and Fryrear, 1996). Glass marbles fill the upper part of the pan above a supporting piece of 1/4-inch-mesh metal screen that rests 3 to 4 cm below the rim. The marbles simulate the effect of a gravelly fan surface and prevent dust that has filtered or washed into the bottom of the pan from being resuspended. Thus, the dust samples represent both wet and dry deposition. The pans are unlikely to overflow in the climate regime of the study area, because a pan holds at least 7 cm of water. According to nearby weather stations, even total monthly precipitation amounts rarely exceed 7 cm. To prevent birds from roosting, dust traps are fitted with two metal straps looped in an inverted basket shape over the pan, and the top surfaces of the straps are coated with Tanglefoot Bird Repellent. (Use of trade names by the

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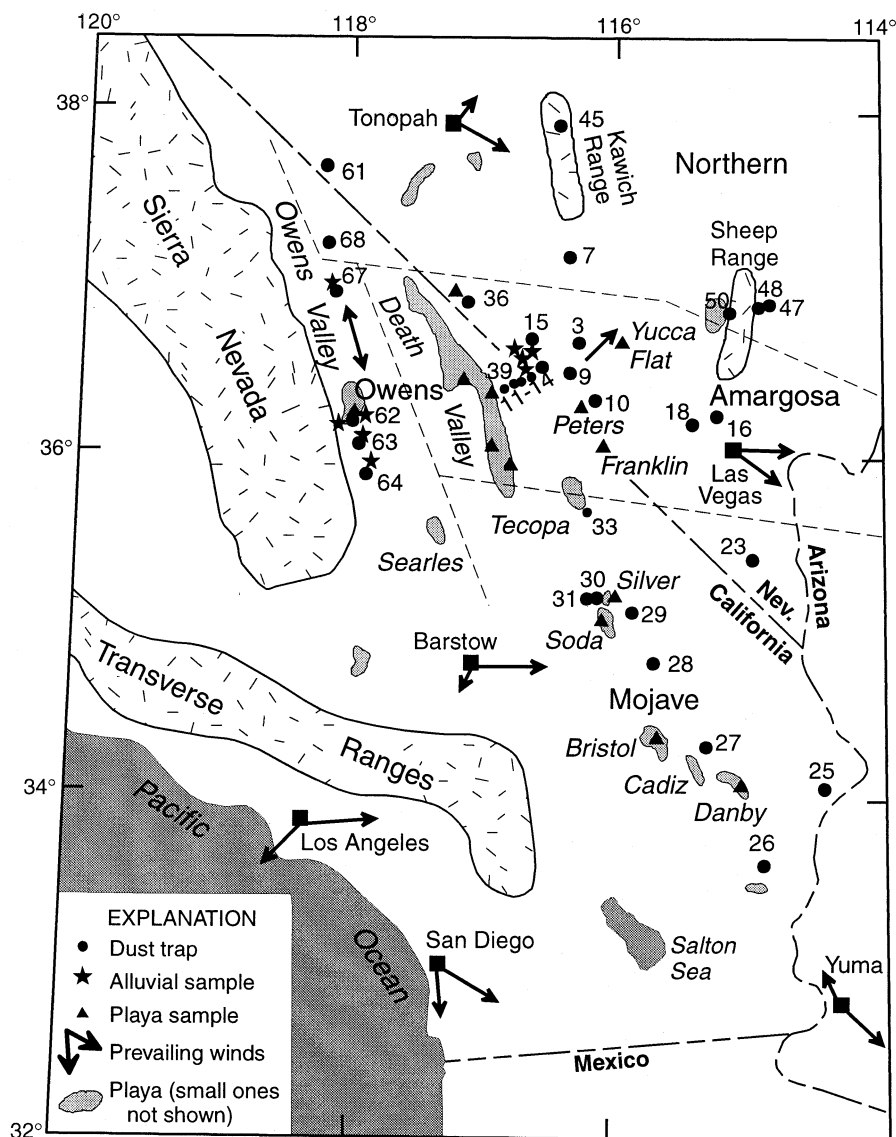


Fig. 1. Map of study area showing dust and sediment sampling sites, dry lake beds, and prevailing winds. Length of arrows is proportional to frequency and strength of annual winds. Dashed lines separate geographic groups of dust traps into northern, Amargosa, Mojave, and Owens Valley.

U.S.G.S. does not constitute an endorsement of the product.) Samples are retrieved by washing the trap components with distilled water into plastic 1-L bottles.

Samples characterized as old (a few thousand years) dust were collected from fine-grained deposits in natural cavities (vugs) formed by weathering in the rhyolite tuffs along the crest of Yucca Mountain between dust-trap sites T3 and T15 (Fig. 1). These vugs are isolated from deposition by alluvial or slope processes; thus, the calcareous, silty sediment within the vugs must have been deposited by eolian processes over a long period of time, possibly as much as several thousand years (Reheis et al., 1997). These samples permit a comparison of modern dust to old dust that accumulated largely before settlement and industrial development.

2.2. Collection of Source Samples

Freshly deposited alluvial and playa sediments are the most likely local sources of dust in the arid southwestern United States (Reheis and Kihl, 1995). We chose the Death Valley-Amargosa region on the

California-Nevada border (Fig. 1) to investigate the effects of nearby potential sources on the composition of dust, because this area has lithologically diverse sediments as well as the highest density of dust-trap sites. We selected sampling sites in active washes on alluvial fans that drained bedrock areas of different lithologic composition. Each lithologic type was represented by four samples collected in different drainages within the same fan complex. About 0.5 kg was scraped from the surface of freshly deposited, fine-grained sediment. The lithologic types included (1) carbonate rocks, chiefly limestone and dolomite with lesser amounts of siliceous rocks, (2) volcanic rocks, chiefly rhyolite with lesser amounts of basalt, and (3) metasedimentary rocks, chiefly schist and calcareous rocks. Four samples were also collected from the Amargosa alluvial plain, a broad expanse of mixed sediment derived from all of the above rock types and a significant local source of dust (Reheis and Kihl, 1995). Source samples also included sediments from the surfaces of many playas in the study area (Fig. 1). D. Muhs and J. Whitney (U.S.G.S.) loaned archived samples from the surfaces of Sarcobatus Flat, Yucca Lake, Peter's playa, and Franklin Playa in the Amargosa area of Nevada and from Silver Lake

and Soda Lake in the Mojave Desert of California. We collected several samples from the floor of Death Valley and from Bristol and Danby Lakes.

Owens (dry) Lake is by far the most important source of dust in the region (Cahill et al., 1996; Reheis, 1997). However, the lake-bed sediments vary spatially in composition (T. Gill, pers. comm.), and many lithologically diverse terrains contribute sediment to the drainages and the lake bed. The Sierra Nevada range west of Owens Valley is dominantly granitic rock; the White-Inyo Range east of Owens Valley is dominantly Paleozoic and Precambrian metasedimentary rocks intruded by diverse plutons; the Owens River headwaters are in the rhyolitic rocks of the Long Valley caldera. Rhyolitic rocks are also abundant in the Coso Range south of Owens Lake. We sampled fresh alluvium from several drainages around the lake and from drainages near dust traps to the south and north (Fig. 1) as well as from playa deposits near site T62.

2.3. Elemental Analyses

In the laboratory, dust samples were dried at $\sim 35^{\circ}\text{C}$ in large evaporating dishes, and coarse organic material was removed. Following analyses of organic and inorganic carbon, soluble salts, and particle size, the remaining sample (if any) was separated into sand and silt-plus-clay ($< 50\ \mu\text{m}$) fractions. In most cases, the processed sample at this point contained no soluble salts or organic matter, because these materials were removed during previous analyses. The $< 50\text{-}\mu\text{m}$ fractions of dust samples were then analyzed for geochemistry (Table 1). Soluble salts and organic matter were not removed from the $< 50\text{-}\mu\text{m}$ fractions of source and old dust samples, because they constituted $< 1\%$ of the samples. Analyses were also performed on selected dust samples that included soluble salts and fine organic matter (Appendix 1).

Analytical techniques included instrumental neutron activation analysis (INAA), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and inductively coupled plasma mass spectroscopy (ICP-MS). Most of the dust samples were analyzed using either INAA or ICP techniques, but some were analyzed using INAA, ICP-MS, and ICP-AES; all source samples were analyzed using only INAA. These three techniques yield results for different but overlapping suites of elements and provide results with different levels of precision (see Reheis et al., 1999 for replicate analytical data). Elements included Ag, Al, As, Au, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Eu, Fe, Ga, Gd, Hf, Ho, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pb, Rb, Sb, Sc, Sn, Sr, Ta, Tb, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn, and Zr. For information on analytical techniques and levels of precision and accuracy, refer to Baedeker and McKown (1987) for INAA, to Briggs (1996) for ICP-AES, and to Briggs and Meier (1999) for ICP-MS. Individual dust samples were usually analyzed separately, but in some cases, samples from adjacent dust traps or from different years or seasons at the same site were combined to obtain enough material for analysis. Complete analytical data for most of the dust samples discussed in this report are available at <http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-99-0531/>.

2.4. Sources of Error

The sampling and processing techniques provide several possible sources of contamination and error in the results. The materials used in the dust traps, including the marbles, the metal mesh on which they rest, the metal of the bird defenses, and the cake pan could potentially contaminate the dust. According to the manufacturer, Tanglefoot contains only polybutene and wax and thus is not a source of metal contamination. Geochemical analyses were conducted on the dust samples after removal of soluble salts and organic matter. The large amounts of soluble and organic material in dusts (10–50% of the total sample) may contain significant amounts of the elements of interest. We conducted many tests to examine these problems.

The silica-glass marbles are essentially chemically inert over the short time span of the study and under normal weathering conditions. Slight pitting developed over several years on the surfaces of marbles at site T39 adjacent to the saltpan in Death Valley and at site T62 on Owens (dry) Lake (Fig. 1). If the pitting is due to solution of silica, it suggests that the pH of rain mixing with dust at these sites may be periodically at least 8.5. Analyses of three pulverized marbles indicate

that most trace elements are present in very small amounts, but notable amounts of As, Ba, Cd, and Cu are locally present (Reheis et al., 1999). However, the amounts of these elements potentially released from the marble surfaces (compared to the measured contents of the crushed whole marbles, which contain color dyes) are probably miniscule.

Galvanized metal screens were used to support the marbles until 1997; these were replaced first by rubber screens, which decayed in less than a year, and then by stainless steel screens. Many of the dust samples contained surprisingly large amounts of Zn with quantities as high as 6%; (Table 1). Analyses of the galvanized material that coats the metal mesh showed that it is almost entirely made of Zn ($> 90\%$) with minor amounts of Cu and Fe (1–10%). Samples taken in the fall of 1997 from Owens Valley and in 1999 from other sites were accumulated in pans with stainless steel screens; these new samples still contained large Zn concentrations of as much as 10% (Appendix 1). We conducted ICP analysis of the stainless steel screens by complete dissolution in hot concentrated HCl and HNO_3 (the material is quite resistant and was slow to dissolve). The analysis showed that the new screens are composed of Fe (71%), Cr (18%), Ni (8.2%), Mn (1%), V (1%), Cu (2040 ppm), Co (1870 ppm), Mo (1060 ppm), and Zn (900 ppm). These screen components apparently did not contaminate the 1999 samples (Fig. 2; Appendix 1), because except for Zn, their concentrations either decreased or remained relatively constant compared to earlier samples.

The nonreactive surfaces (Teflon and enamel) of the cake pans provide no source of contamination, but can potentially cause a carry-over effect due to adhesion of dust particles on the surfaces. Using 30 mL of 1% nitric acid, we rinsed the surfaces of several pans that had been used in the field for many years as well as the coated pan used in washing the marbles. The resulting solution contained between 80- and 2500- μg Zn, but no other elements in significant amounts. We conclude that Zn contents of dust samples reflect Zn contamination before 1997 as well as actual variation in dust composition and do not further discuss the Zn data.

We analyzed scrapings of the metal beneath the pan coatings. The only elements present in significant amounts relative to the dust analyses were Al (major), Cu (866 ppm), and Cd (96 ppm); small amounts of Fe (4960 ppm) and Ca (1360 ppm) were also present. Two dust samples, T35-95 and T64-0596 (see data in Reheis et al., 1999), showed anomalously high values of Sn, 850 and 2900 ppm, respectively, compared to < 22 ppm for all other samples. Sn values from these samples were discarded from the database.

A comparison of processed (salts and organic material removed from the $< 50\text{-}\mu\text{m}$ fraction) and unprocessed dust samples (Fig. 2; Appendix 1) shows that the soluble and organic fractions contain significant amounts of K and P, and for samples from T62 on Owens (dry) Lake, As, Sb, and sometimes Li; other elements are present in very low amounts. Thus the processed dust samples may be missing 20 to 60% of the original As content and 20 to 30% of the Sb content, elements of particular interest in the results of this study. Comparisons between dust and source samples (which included very small amounts of salts and organics) need to consider these depletions. To maintain consistent comparisons, unprocessed dust samples are not included in the statistical analyses but do appear in some figures in the following discussion.

2.5. Numerical and Statistical Analyses

To avoid closure problems and to facilitate a comparison to other studies, we used element ratios rather than concentrations in statistical analyses. Most atmospheric-dust studies calculate ratios relative to Al. However, Al is not usually analyzed by the INAA technique; its use would have resulted in rejection of over half of the dust data. Thus we chose to calculate ratios relative to Fe. We also compared element enrichments in dust samples relative to average crustal composition (enrichment factor, e.g., Galloway et al., 1982) using Fe as the reference element (crustal abundance data from Krauskopf and Bird, 1995).

Multivariate statistical analyses using element/Fe ratios were performed to reduce and clarify the relations among dust and possible source samples in different geographic areas. Dust samples are grouped geographically as follows (Fig. 1): sites in Owens Valley (T62–67), sites in the Amargosa area in and east of Death Valley (T3, T9–18, T36, and T39), sites in the Mojave Desert south and east of Death Valley (T23–33), and sites north of Death Valley and Las Vegas (T7,

Table 1. Mean values for selected elemental analyses of the <50µm fractions of dust (salt and organic fractions removed) and source samples (data for dust samples from Reheis et al., 1999). [Fe, Ca, Na, K, and Mg in percent; all others, listed in alphabetical order, in ppm. Alluvial and playa samples analyzed by INAA. Dust samples analyzed by INAA, ICP-MS, and ICP-AES.]

Samples	Fe	Ca	Na	K	As	Ba	Cd	Ce	Cr	Cs	Eu	La	Li	Mn	Nd	Ni	Pb	Rb	Sb	Sr	Th	U	W	Zr	Zn
Dust samples by geographic area																									
Amargosa (<i>n</i> = 20) ^a	3.4	<u>3.1</u> ^b	<u>2.3</u>	2.5	23	1150 ^c	1.4	82	<u>84</u>	7.9	1.0	42	61	<u>560</u>	32	<u>51</u>	<u>170</u>	125	<u>6</u>	304	12.1	3.4	<u>3.0</u>	200	10000
E. Mojave (<i>n</i> = 21)	3.9	<u>2.7</u>	2.0	2.4	<u>14</u>	748	<u>1.8</u>	101	<u>90</u>	6.8	1.1	53	<u>64</u>	<u>650</u>	39	<u>60</u>	<u>180</u>	131	3	306	13.3	3.4	2.8	230	10400
Northern (<i>n</i> = 15)	3.0	<u>3.1</u>	2.4	2.3	21	<u>797</u>	9.3	77	<u>61</u>	<u>7.6</u>	0.9	39	56	580	29	<u>50</u>	<u>290</u>	118	8	<u>325</u>	11.6	<u>3.7</u>	4.2	180	20700
Owens T-62 (<i>n</i> = 7)	2.6	6.8	<u>3.9</u>	2.3	<u>20</u>	<u>1250</u>	0.9	44	<u>26</u>	11.	0.6	24	610	610	17	<u>28</u>	180	119	9	960	14.7	<u>4.2</u>	3.5	69	13100
Owens other (<i>n</i> = 5)	2.6	<u>2.7</u>	2.5	1.6	<u>37</u>	3750	0.5	50	41	7.2	0.7	25	550	660	21	<u>54</u>	360	86	11	<u>389</u>	11.7	4.7	3.7	<u>180</u>	27800
“Old” dust (<i>n</i> = 8)	4.4	2.6	1.6	3.0	11	584		111	66	9.2	1.2	55			45	<u>30</u>		164	2	280	20.5	4.7	58.	<u>280</u>	<u>293</u>
Amargosa alluvial samples by primary lithology																									
Limestone (<i>n</i> = 3)	3.3	13.	<u>3.0</u>	2.3	15	580		87	42	5.3	1.0	44			36	24		95	<u>6</u>	248	14.0	3.3	1.8	<u>340</u>	87
Volcanic (<i>n</i> = 3)	4.4	2.9	<u>2.7</u>	3.3	<u>17</u>	645		105	48	8.5	1.2	53			41	20		151	<u>2</u>	291	20.2	4.4	<u>4.5</u>	<u>370</u>	<u>129</u>
Metased. (<i>n</i> = 4)	4.7	5.8	<u>2.5</u>	3.6	13	700		105	60	8.1	1.4	53			43	29		138	2	322	17.6	4.0	<u>2.5</u>	350	100
Mixed (<i>n</i> = 4)	4.3	<u>7.8</u>	2.5	3.2	17	614		98	48	<u>11.</u>	1.2	49			40	28		142	<u>3</u>	304	17.2	3.7	2.7	<u>280</u>	99
Owens Valley alluvial samples by geographic area																									
Sierra Nev. (<i>n</i> = 4)	4.8	3.7	2.3	2.4	5	884		<u>120</u>	<u>46</u>	5.7	1.8	<u>62</u>			51	<u>27</u>		139	<u>1</u>	444	<u>27.2</u>	12.	5.1	<u>520</u>	174
Volcanic (<i>n</i> = 3)	<u>4.8</u>	4.8	1.2	2.4	19	625		87	50	<u>7.6</u>	1.3	45			36	32		132	<u>2</u>	280	16.9	4.3	6.0	380	126
Inyo Range (<i>n</i> = 3)	4.5	<u>3.7</u>	1.7	2.3	<u>14</u>	669		113	51	6.0	1.6	59			49	21		116	2	358	23.4	6.2	6.1	<u>730</u>	121
Lake margin (<i>n</i> = 3)	4.7	<u>6.0</u>	1.7	1.9	<u>25</u>	545		86	<u>69</u>	12.	1.2	46			35	<u>55</u>		108	<u>5</u>	<u>643</u>	24.7	5.5	5.1	<u>350</u>	126
Playa samples																									
Owens Lake (<i>n</i> = 2)	4.8	3.0	2.7	3.6	17	993		52	35	18.	0.8	30			22	31		232	4	328	20.2	4.1	3.7	78	186
Amargosa (<i>n</i> = 6)	3.5	<u>10.</u>	2.0	3.5	12	<u>696</u>		85	38	<u>7.9</u>	1.0	42			34	21		131	<u>1</u>	<u>680</u>	15.1	4.3	<u>2.5</u>	<u>230</u>	<u>79</u>
Death Valley (<i>n</i> = 8)	3.6	<u>5.5</u>	2.0	2.3	<u>18</u>	<u>617</u>		<u>98</u>	<u>55</u>	5.5	1.4	<u>50</u>			<u>43</u>	<u>26</u>		123	<u>2</u>	<u>513</u>	16.3	<u>4.8</u>	6.1	<u>420</u>	<u>106</u>
Silver-Soda (<i>n</i> = 4)	<u>5.4</u>	6.6	<u>2.9</u>	2.5	<u>9</u>	676		114	42	<u>4.1</u>	1.6	60			49	20		102	1	<u>698</u>	21.8	6.2	2.9	<u>420</u>	<u>76</u>
Bristol Lake (<i>n</i> = 4)	5.7	5.3	2.5	3.0	12	487		112	53	7.0	1.5	58			49	<u>22</u>		148	1	<u>446</u>	19.3	4.8	2.8	<u>340</u>	132
Danby Lake (<i>n</i> = 4)	5.4	<u>3.5</u>	3.3	2.8	8	598		104	52	5.6	1.6	54			48	<u>23</u>		120	1	<u>366</u>	16.1	<u>5.3</u>	2.1	330	123

^a *n* number of samples.

^b Underline indicates standard deviation >30 % of mean.

^c Bold font indicates standard deviation > 70 % of mean.

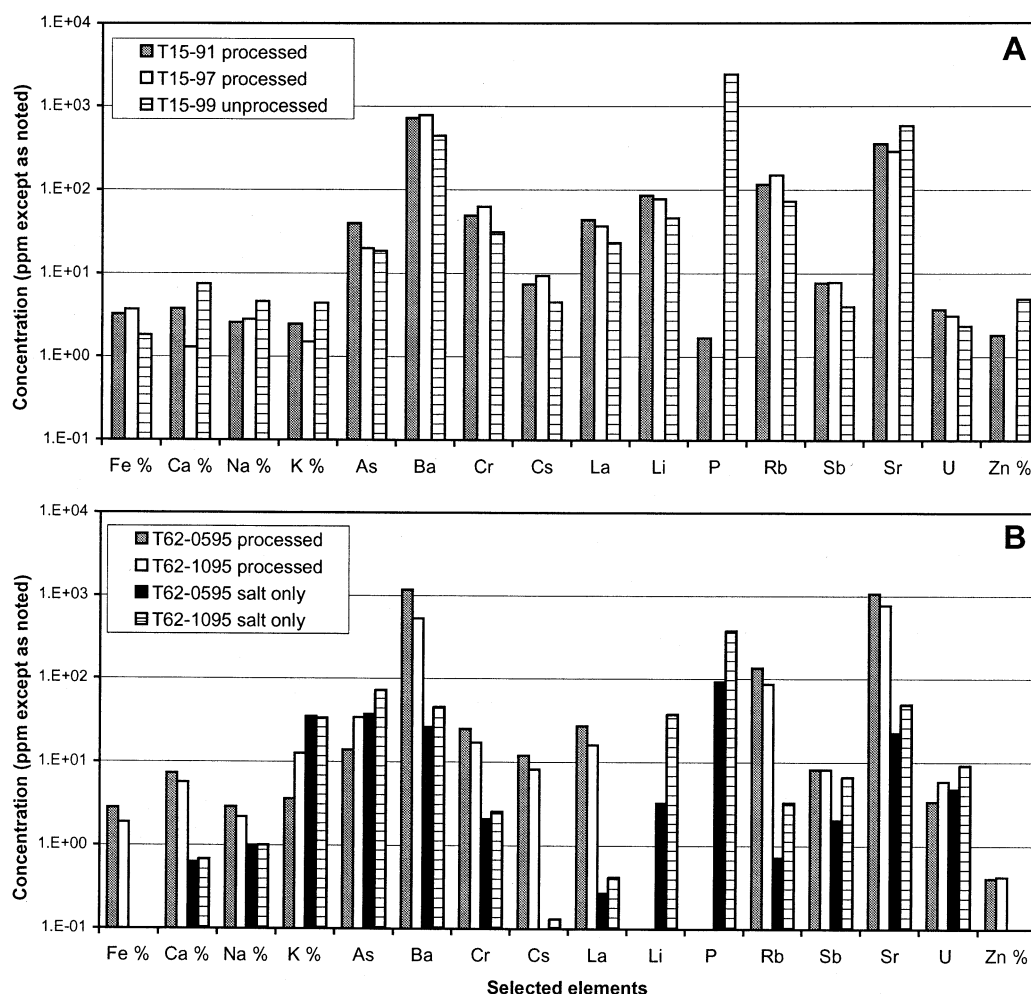


Fig. 2. Graphs comparing element concentrations obtained by analysis of the $< 50\text{-}\mu\text{m}$ size fractions of processed (i.e., organic and soluble-salt fractions removed), unprocessed (including organic and soluble-salt fractions), and soluble-salt samples (see Appendix 1 for detailed comparison). T15: site in Amargosa area; T62: site on Owens lake bed.

T45–50, T61, and T68). We used standard statistical routines in SPSS, a PC-based statistical package (SPSS, 1997). Tests of normal distributions showed that only 25% of element concentrations were normally distributed using all dust samples, whereas $\sim 75\%$ were normally distributed when separating samples into geographic areas. Thus we took the conservative approach of using nonparametric statistical techniques (Reimann and Filzmoser, 2000). Cluster analysis showed relations among elements from dust and source samples. The Mann-Whitney U test and the Kruskal-Wallis H test were used to test whether independent samples (such as dust vs. source samples or dust samples from different geographic areas) were from the same population. These tests incorporate both central tendency and dispersion; thus, a population with a large range of values may be statistically different than one with a small range even if their modes or averages are similar. Samples are assumed to be from different populations when significant levels are $< 5\%$.

Because not all the dust samples were analyzed using the same methods, the dataset is not uniform (i.e., ICP-AES yields minimum-limiting values of Au, Eu, and Ho in low concentrations, and INAA does not usually yield values of Br, Ga, Li, Mg, Mn, and Pb). In rock-forming minerals, many major and trace elements substitute for or are strongly associated with each other (such as the well-known associations of Ca-Mg-Ba-Sr, Na-K-Rb-Cs, Th-U, Zr-Hf, and rare-earth elements). The cluster analyses of dust samples confirmed many of these associations but show interesting anomalies for some elements. Thus, the following discussion focuses on a subset of elements that are

common to both ICP and INAA and that are representative of these associations and anomalies rather than using the entire dataset. Data for selected other elements of interest that are not common to the whole dataset, such as Li, Mn, and Pb, are also presented.

3. RESULTS

We used several approaches to decipher the relations among dust and potential source samples. These included (1) a comparison of dust and source compositions using both area averages and pairs of dust and source samples, (2) transects showing changes in dust composition with distance downwind of sources, and (3) a comparison of modern dust to old dust in the Amargosa area.

3.1. Element Concentrations and Associations in Dust and Source Samples

A comparison of elemental analyses of dust and potential source samples shows that the compositions of modern dusts and source samples are statistically similar for many elements across the whole study area but are different for other elements. Concentrations of the major elements Fe, Na, and K in dust

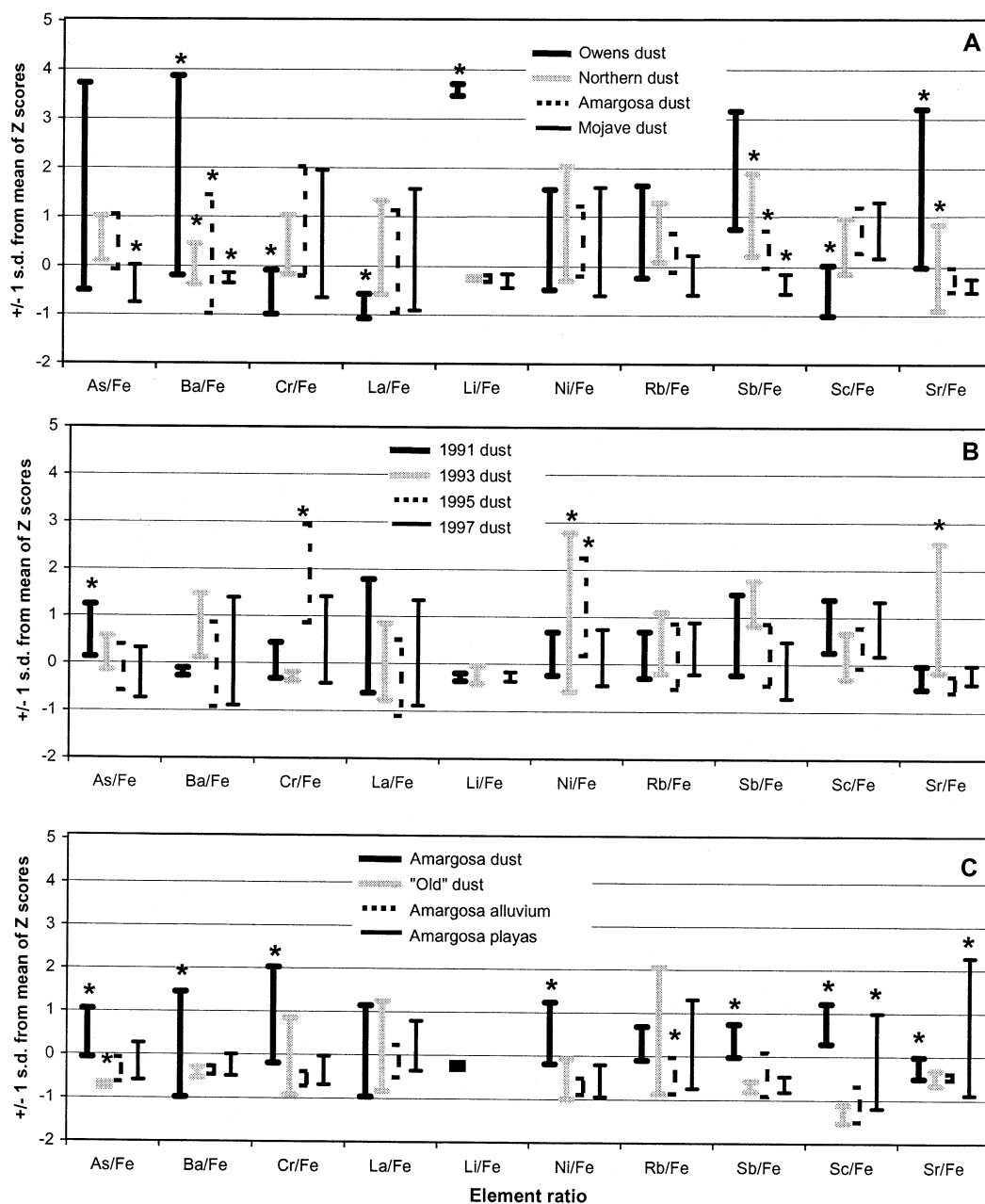


Fig. 3. Graphs showing standard deviations of Z scores of mean element/Fe ratios for (A) modern dust samples from different geographic areas, (B) modern dust samples from all areas collected in different years, and (C) modern dust, old (a few thousand years) dust from Yucca Mountain, and local source sediments in the Amargosa area. Asterisk indicates that the population or pair of populations represented by the range below the asterisk is significantly different (at < 0.05 level, based on nonparametric analysis) from the other populations for a given element ratio.

samples (with soluble salts removed) are similar to those in the source samples (Table 1); however, Na content is higher in dust samples including salts than in those without salts (Fig. 2; Appendix 1). This implies that the proportion of common rock-forming minerals in the dust is the same as that in the sources, and that salt is a significant contributor of Na. Most dust samples are enriched in As, Cr, Ni, and Sb relative to source samples (Table 1; Figs. 3C, 4); dusts are depleted in elements associated with heavy minerals such as Hf, Sc, Th, Zr, and certain rare earths. Significant differences exist in contents

of As, Ba, Cr, Sb, Sc, Sr, and rare-earth elements among modern dust samples from different geographic areas (Figs. 1, 3A, 4), especially between dust from Owens Valley and that from other areas.

Some elements in dust samples vary considerably in concentration from year to year, whereas others remain relatively constant (Figs. 3B, 5). For example, As and Sb ratios relative to Fe were higher in 1991 than in later years. Because concentrations of As and Sb are higher in Owens Valley dusts than elsewhere (Figs. 3A, 4C), these results suggest that dust from

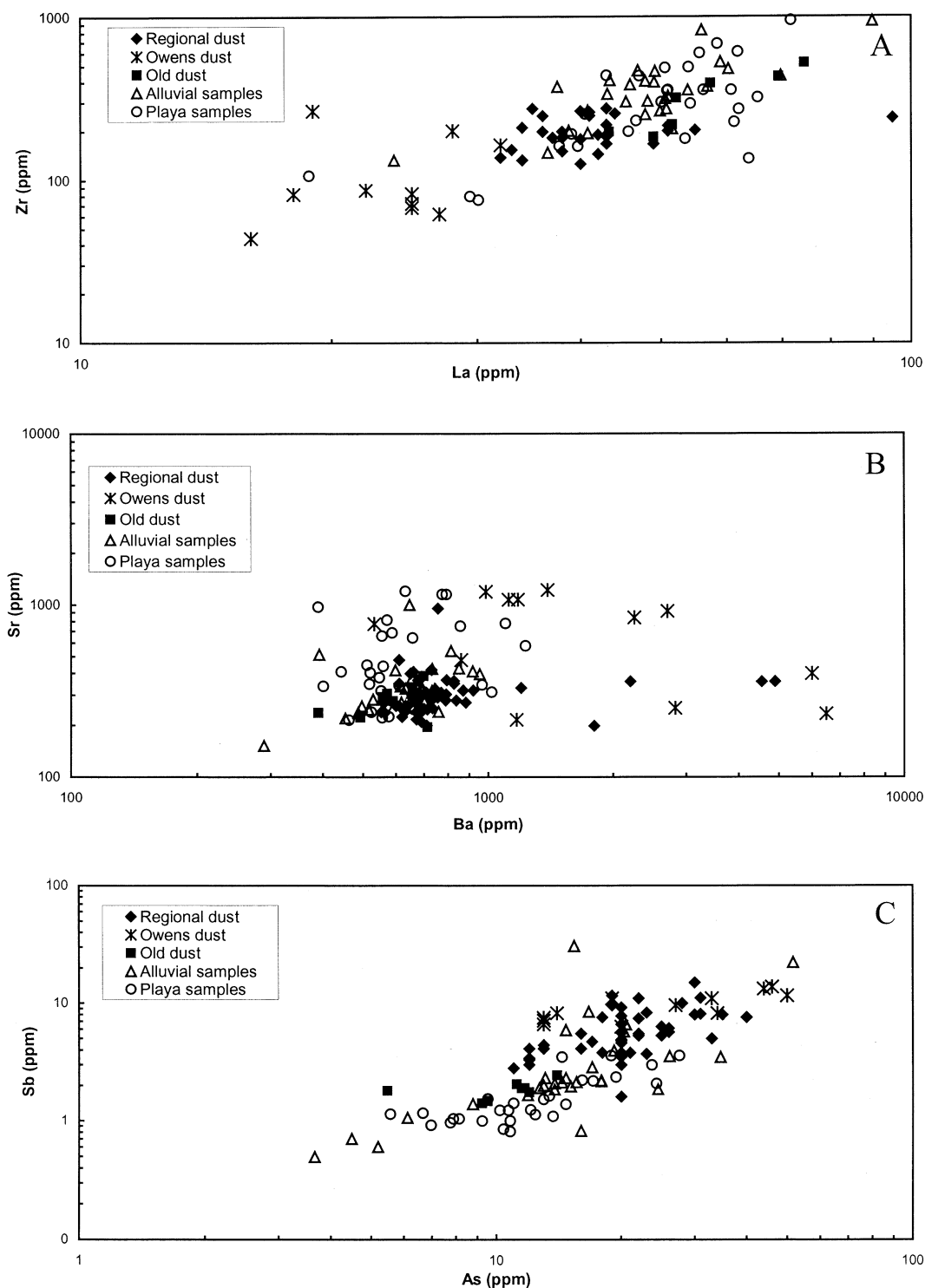


Fig. 4. Scatterplots of selected trace elements for dust and local-source samples. Note that old dust samples from Yucca Mountain are more like alluvial- and playa-sediment samples than like modern dust. (A) Zr, and La represent alluvial sediment and some playas (especially Soda Lake). (B) Sr represents calcareous sediment, mainly playas, whereas Ba is uniquely high in Owens dust. (C) As and Sb show strong association with Owens dust.

Owens Valley forms a larger proportion of regional dust samples in 1991 than in other years. In contrast, Cr/Fe was highest in 1995, and Ni/Fe was high in 1993 and 1995, yet Cr and Ni are not preferentially enriched in dusts from a particular area.

The composition of modern dust sampled at site T62 on the bed of Owens (dry) Lake is distinctive (Table 1; Figs. 3A, 4), especially in samples accumulated during winter when dust is produced in large quantities from the lake bed through a com-

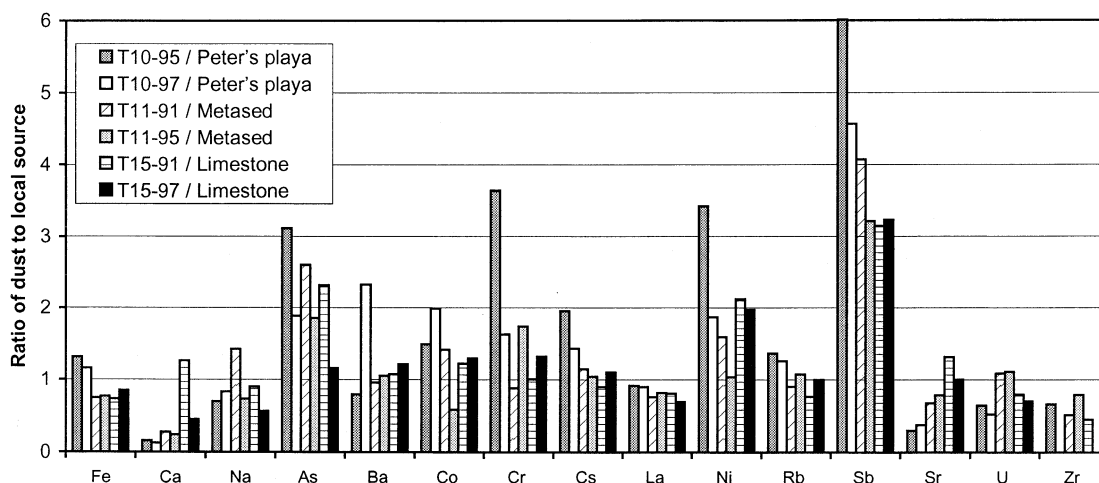


Fig. 5. Graphs comparing ratios of elements in modern dusts and local sources in Amargosa area at individual sites in different years. T10, T11, and T15, sites in Amargosa area; metased, alluvium derived from metasedimentary rocks; limestone, alluvium derived from calcareous rocks.

bination of salt hydration and powerful winds (Saint Amand et al., 1986; Reheis, 1997). This dust is enriched in Sr ($\times 3$), As and Sb ($\times 2$, accounting for amounts in the salt fraction), and Li ($\times 10$) relative to regional dust samples. Dust samples from elsewhere in Owens Valley also are enriched in Ba ($\times 2$ – 3) and Pb ($\times 2$). Dust in Owens Valley is strongly depleted in all rare-earth and other heavy elements relative to other dust and to many of the source samples.

Cluster analysis provides insight into possible sources of dusts but not the relative proportions of sources in the dusts. There are four main clusters of elements in the dust samples:

- (1) Rare-earth elements, Zr and Hf, and Au, W, Sc, and Ta. The rare earths, Zr, and Hf are also clustered in alluvial and playa samples (Fig. 4A). This grouping suggests that these elements represent heavy minerals derived from one or both sources.
- (2) Ca-Sr, K-Rb-Cs, and U-Th. This cluster consists mainly of lithophile elements abundant in rock-forming minerals, such as feldspars and micas, and also elements abundant in carbonate-rich playas (Fig. 4B).
- (3) As, Ba, and Sb. These elements do not form a cluster in the alluvial and playa samples, but they are notably higher in concentration in Owens Valley dust than in dust from other regions (Figs. 3A, 4; Table 1).
- (4) Cr and Ni. These elements cluster with other metals in alluvial and playa samples. In dusts, elements in the latter two clusters are commonly attributed to anthropogenic emissions combined with lesser amounts of natural dusts (e.g., Galloway et al., 1982; Church et al., 1990). Geologically, such elements also characterize metal ore deposits, especially sulfides and carbonates (Franklin et al., 1981; Hale, 1999) and are also notable components of volcanic gases (e.g., Hinkley et al., 1999b).

3.2. Comparison of Dust Samples to Possible Source Samples

Several dust-trap sites lie adjacent to or directly downwind from sites where alluvium and playa samples were collected to

characterize the composition of local sediment sources (Fig. 1). Ratios of dust sample compositions to those of potential local sources provide insight into (1) the relative contribution of playas and alluvium to nearby deposited dust, (2) annual variation in dust composition, and (3) possible sources of dusts at site T62 on Owens (dry) Lake. However, we note that these insights depend on the untested assumption that the mineral components containing elements of interest are the same in dust and source samples.

Elements that are generally concentrated in dusts relative to local source sediments in the Amargosa area include As, Ba, Co, Cr, Ni, and Sb; elements that are depleted in these dusts include Fe, La and other rare earths, Rb, and Zr (Figs. 4, 5; Appendix 2). Some elements show distinct annual variations in ratios of dust relative to local sources (Fig. 5). For example, at sites T10, T11, and T15, there are large annual differences in ratios of As, Co, Cr, Ni, and Sb. These temporal differences suggest that (1) annual amounts of dust derived from a local source vary, probably depending on precipitation and consequent vegetation changes, and/or (2) annual contributions of dust from distant sources vary, depending on environmental factors and on shifts in dominant regional wind patterns or in large, long-distance dust events.

Plots of element ratios commonly used in discussions of upper crustal composition (e.g., Taylor and McLennan, 1985), such as Th/U, Rb/Sr, and La/Th (Fig. 6) show that modern dust samples throughout the region are similar in composition but are different from Owens Valley dust. With respect to these elements, the regional dusts appear to be a mixture of playa (lower in Th/U) and alluvial (higher in Rb/Sr) sources. The composition of dust deposited at site T62 on Owens Lake during the winter is distinctively low in values of Rb/Sr (reflecting high Sr content) and La/Th (depleted in La and other rare earths); of the potential dust sources sampled, it is closest to the average composition of three lake-marginal alluvial samples collected east and north of T62. It is also similar to the adjacent lake-bed samples in La/Th and Th/U values.

Changes in dust composition along a transect indicate contributions of local source sediment of variable composition

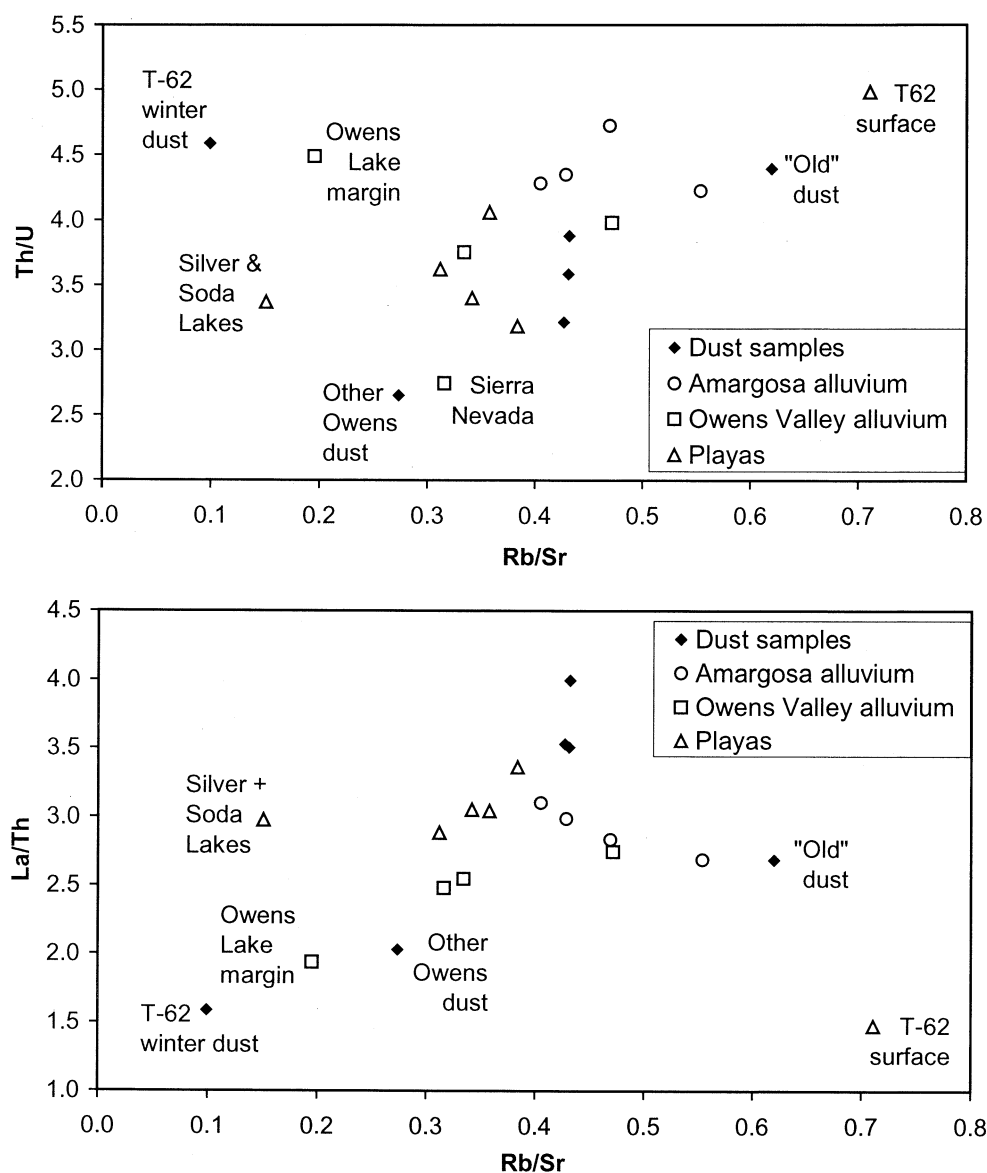


Fig. 6. Graphs showing average ratios of Th/U and La/Th vs. Rb/Sr for modern dust, old dust, and source samples, grouped in different geographic areas.

(Fig. 7). The Death Valley transect of dust traps reveals changes in dust flux and composition across the topographic barrier of the Funeral Range downwind (northeast) of the salt-rich mudflats on the floor of Death Valley. Northeast of the Funeral Range crest, the transect sequentially crosses over alluvium (Amargosa alluvial samples; Table 1) derived from (1) metasedimentary rocks on the east flank of the Funeral Range (SO-MS; Fig. 7), (2) mixed lithologies on the floor of Amargosa Valley (SO-X), and (3) limestone and dolomite on the southern side of Bare Mountain (SO-LS). Note that the dust data in Figure 7 are all from samples collected in 1991, so that changes with time can be ruled out.

The most obvious pattern in elements along the transect is in Sr, which decreases in dust samples downwind from high values in Death Valley playa sediment (Fig. 7A) with little input from alluvial sources. Dust samples are generally higher

in As, Ni, and Sb (not shown) than the sampled sources. Alluvium derived from metasedimentary rocks of the Funeral Range is higher in Cr than other alluvial samples, and dust in this area (T-39) is also higher in Cr. Elements associated with aluminosilicate minerals, such as Rb, Ce, and Zr, are enriched in the alluvial samples derived from metasediments and mixed lithologies as well as in nearby dust samples (Fig. 7B).

Because dust collected in Owens Valley is enriched in several elements relative to regional dust samples (Table 1; Figs. 3A, 4), these elements might be useful as tracers to identify the proportion of Owens Valley dust present in the region. Correlations indicate that distance from Owens (dry) Lake is significantly related to decreases of As, Ba, Li, Mg, Sb, and Sr; however, the correlations of Li, Sr, and Mg with distance are weak (not shown). Relations of As, Ba, and Sb with distance are highly significant (Fig. 8; Ba not shown); if the T62 samples

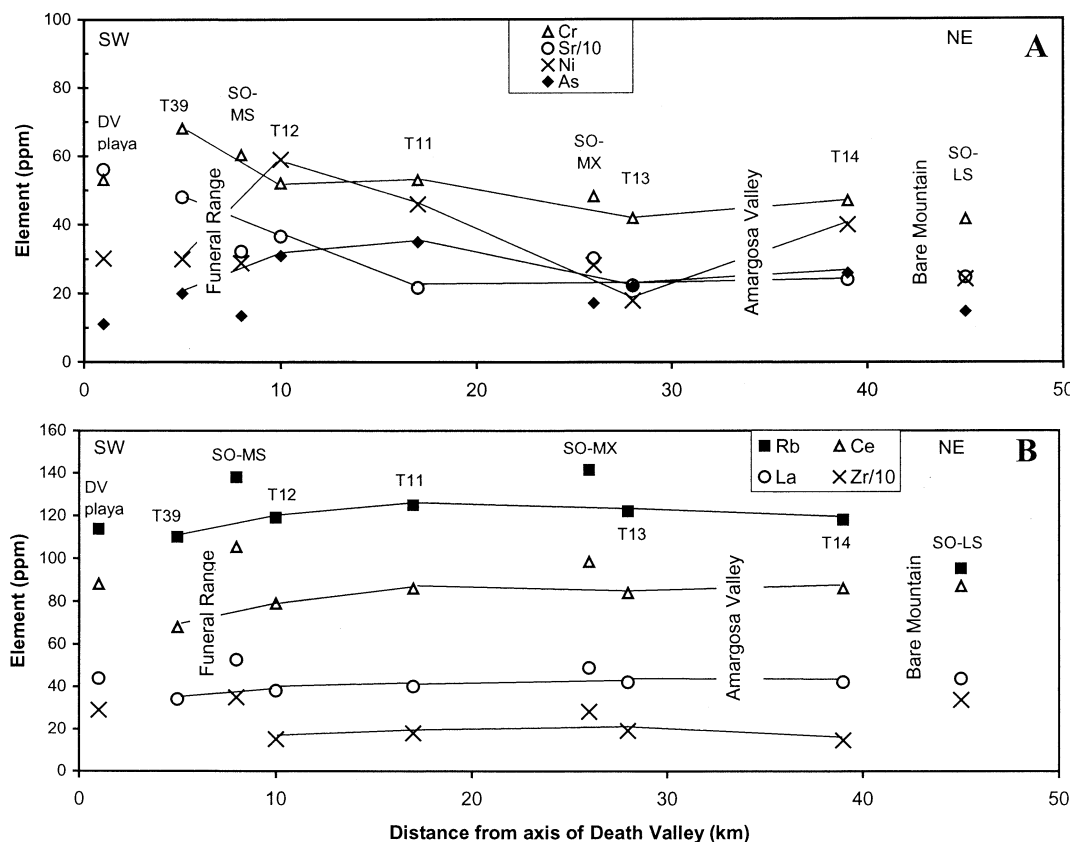


Fig. 7. Plots showing trace element concentrations of dust and source samples along the Death Valley transect, trending northeast and generally downwind from Death Valley playa into the Amargosa Desert (Fig. 1). T-: dust sampled collected in 1991. Points represented by letters are source samples: DV, Death Valley playa; SO-MS, metasedimentary alluvium; SO-MX, mixed-lithology alluvium; SO-LS, limestone alluvium.

are removed from the data (points plotted at 0 on the x-axis), r^2 values for logarithmic regressions (log of concentrations) increase to 0.49 for As and 0.34 for Sb. The greater variability of element concentrations near the putative source, and especially the lower concentrations at T62 on Owens Lake playa, are likely due to the variability of element concentrations on and around the lake bed as well as contributions of other sources in southern Owens Valley that are enriched in As and Ba (discussed below).

3.3. Old Yucca Mountain Dust

Samples of dust that accumulated in natural cavities or vugs along the crest of Yucca Mountain (west of T3; Fig. 1) represent dust that probably accumulated over as much as several thousand years (Reheis et al., 1997) and is far less influenced by historic deposition, i.e., over the past 200 yr. Thus these old dust samples provide an invaluable reference to gauge the influence of recent changes in human activity in the desert and anthropogenic emissions on dust composition in the study area.

For most of the elements examined (Figs. 3C, 4; Table 1), the old dust samples are nearly identical to or overlap with samples of modern eolian dust collected from sites in the Amargosa region. Some of the samples are slightly enriched in crustal elements such as Fe, K, Rb, and rare earths with respect to

modern dust. We interpret this enrichment as caused by additions of K-rich weathered tuff from the vug walls. Sand-sized subangular quartz, K-feldspar, and mafic fragments seen in petrographic examination (Reheis et al., 1997) confirm the presence of vug-wall contaminants in the dust.

Some of the vug fillings, as much as 6-cm thick, were subsampled by depth to see if they are stratified. A comparison of samples from the tops and bottoms of these fillings (not shown) indicates little difference in element content with depth, except that some of the elements associated with heavy minerals (e.g., Fe, Zr, and most rare earths) are slightly more concentrated at the bottom of the fillings. These relations indicate that either there has been little change through time in the composition of dust accumulating in the vugs or the fillings are well mixed by burrowing insects and by wetting and drying cycles.

Old dust from Yucca Mountain is distinctly lower in As, Ba, Cr, Ni, Sb, Sc, and Sr contents relative to modern dust from the Amargosa region (Fig. 3C), indicating differences in source area for dust deposited in the geologic past. As, Ba, and Sb all decrease downwind of Owens (dry) Lake (Fig. 8), and Ba is particularly enriched in source sediments from Owens Valley (Table 1). These results suggest that Owens Valley was not an important source during deposition of the old dust. In contrast,

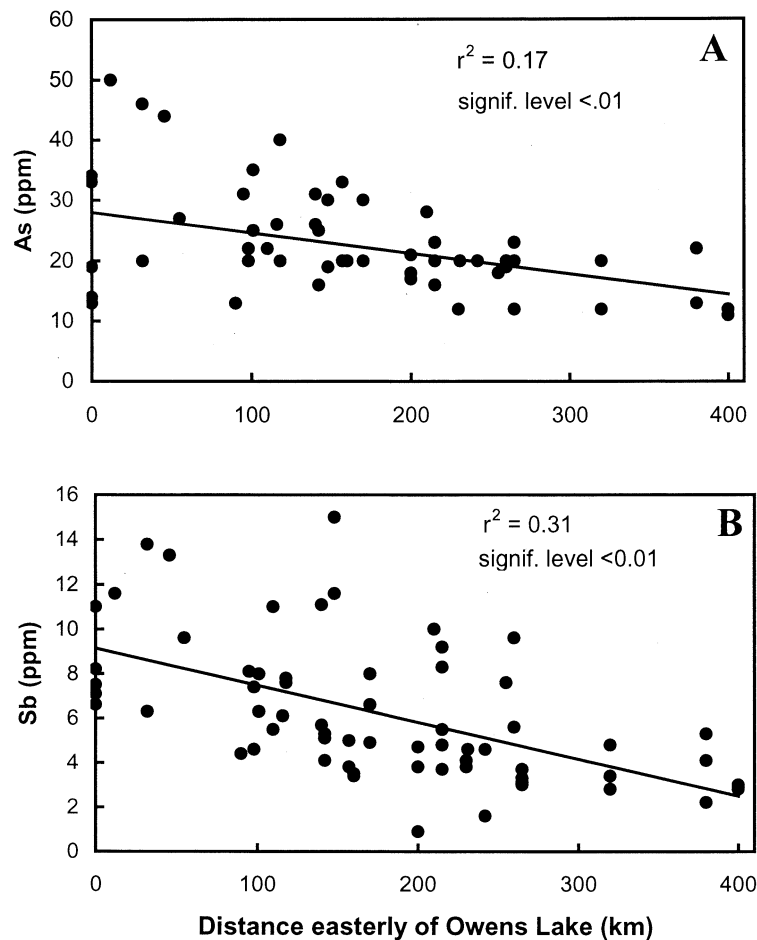


Fig. 8. Scatterplots showing selected element concentrations of modern dust samples relative to distance from Owens (dry) Lake. Linear regression using all points yields the indicated r^2 values and significance levels. Exclusion of points from site T62 (plotted at 0 km on the x-axis) increases r^2 values for logarithmic regressions to 0.49 for As and 0.34 for Sb.

elevated Cr and Ni in modern dust may reflect more distant sources. Element ratios (Fig. 6) suggest that old dust is somewhat depleted in Sr and U; these mobile elements may be lost by overflow or leaching from vug depressions during wetting events.

4. DISCUSSION

A comparison of elemental analyses of dust and potential source samples in the study area shows that modern dusts have compositions that are generally similar with respect to many elements across the whole study area, with certain exceptions discussed below, and that these compositions are distinct from those of most source samples with respect to several key elements. More specifically, our results show that (1) all dust samples are enriched in As, Cr, Ni, and Sb relative to source samples (Table 1; Figs. 3C, 4); (2) on average, dusts are depleted in elements such as Fe, Hf, Sc, Zr, and certain rare earths compared to source samples; (3) there are significant differences in contents of As, Ba, Li, Mg, Sc, Sr, and rare-earth elements between modern dust samples from Owens Valley and dust from other areas.

4.1. Relative Contributions of Alluvium and Playa Sediments

A comparison of dust samples at specific sites with local sources (Figs. 3C, 7) suggests that playa sediment is an important source of Sr (a proxy for Ca and perhaps U) in dust and that alluvium is a source of La (and other rare earths), Rb (and K), and perhaps Th. Elements found in heavy minerals (Fe, Hf, Sc, Zr, and many rare earths) decrease in abundance as follows (Table 1): Mojave playas + Owens Valley alluvium > Amargosa alluvium + playas > regional dust (Mojave, Amargosa, northern) > Owens dust + Owens (dry) Lake. We interpret these changes in abundance to indicate winnowing of heavy minerals derived from alluvium by eolian transport.

Although our dust samples are depleted relative to local sources in elements associated with heavy minerals, they are similar or slightly enriched relative to average continental crust (see Eu, Hf, and La in Fig. 9A). Ratios of La/Th (Fig. 6) in dust samples outside of Owens Valley are ~3.5 to 4.0, and Owens Valley dust has much lower ratios (1.5–2.0). These crustal enrichment values are similar to those for rare-earth elements in loesses (Taylor et al., 1983), but the La/Th ratios are much

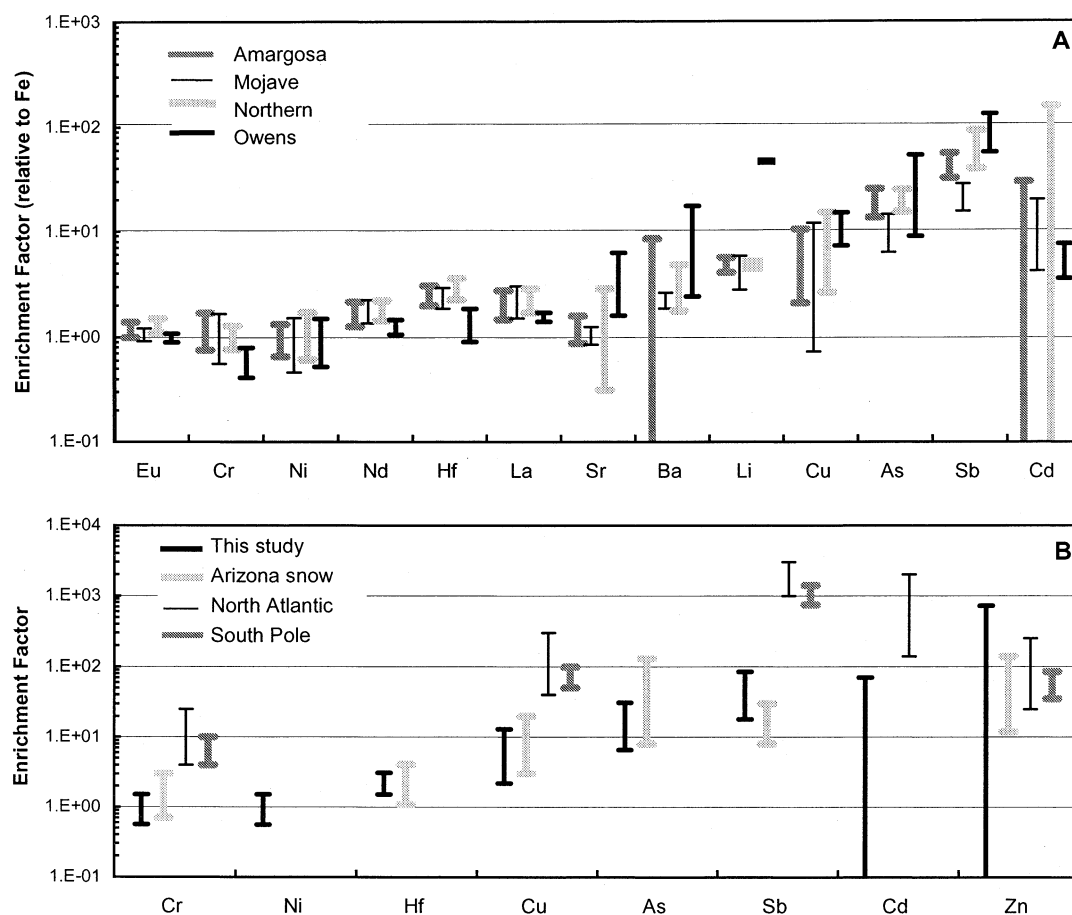


Fig. 9. A comparison of selected element enrichment factors (calculated relative to Fe) for (A) dust samples from different geographic areas of this study and (B) average dusts from this study and data from other studies. Bars for dust samples of this study show range of ± 1 standard deviation from the mean. Bars for dust from Arizona snow samples represent range of all samples estimated from Fig. 8 of Barbaris and Betterton (1996). Bars for dust from North Atlantic Ocean near Bermuda and from the South Pole represent ± 1 geometric standard deviation estimated from figure in Duce et al. (1975; p. 60).

more variable than those obtained for worldwide loesses (~ 2.8 , identical to that of continental crust) by Gallet et al. (1998). At least two factors may contribute to the differences between modern dust in the study area and loess: (1) Our dust samples are finer-grained (only 10–25% of particles in the 20–50 μm size range) than the loess samples analyzed by Taylor et al. (1983). Consistent with our results, Muhs and Bettis (2000) found that Zr in Peoria loess decreases downwind due to depletion of the coarse silt fraction in which Zr concentrates. (2) Our dust samples are less well mixed than most loess, especially those dusts sampled close to a distinctive source such as Owens Lake.

Contributions of dust from alluvial and playa deposits are shown graphically by the Death Valley transect (Fig. 7). A playa source is indicated for Sr, which decreases in dust samples downwind from the floor of Death Valley. Elevated Cr in dust may in part be derived from minerals found in the meta-sedimentary rocks of the Funeral Range. Some elements associated with aluminosilicate minerals (such as Ce, Rb, and Zr) show slight increases in dust samples adjacent to alluvial sources that likely reflect the input of silt and clay from the

Amargosa Valley. These results are consistent with conclusions of Reheis and Kihl (1995), who found that Death Valley is a significant source of soluble salts and carbonates and that the broad, flat, lightly vegetated alluvial plain of the Amargosa Valley contributes more silt and clay.

4.2. Contributions From Specific Sources

4.2.1. Owens Valley: Owens (dry) Lake and nearby alluvium

Most of the dust in Owens Valley, especially in winter, is derived from or near the lake bed (Reheis, 1997). Sites far from the lake bed, such as T66 and T67 (Fig. 1) show the influence of local dust sources. Note, for example, that “Other Owens dust” in Figure 6 is similar to alluvial samples from Sierra Nevada drainages in ratios of Rb/Sr and La/Th. Dusts in Owens Valley have higher concentrations of As, Ba, Li, Sb, and Sr than dust samples from other areas (Fig. 3A). The highest concentrations of As and Sb are found in Owens Valley alluvium and lake-marginal deposits away from the dry bed of Owens Lake (Tables 1, 2). These relations suggest that Ba, Li,

Table 2. Comparison of selected elemental contents (ppm except where noted) of aerosol, dust, and source sediments in Owens Valley. [—, below detection level for method used. N.D., not measured; N.R., not reported due to sample contamination by collection apparatus]

Sample type and area collected	Reference	As	Ba	Li	Pb	Sr	Zn
Aerosol, high mass non-storm (fall)	Cahill et al., 1994	—	N.D.	N.D.	300	1000	1000
Aerosol, S sand sheet, spr. 1993	Cahill et al., 1994	100	N.D.	N.D.	100	—	400
Aerosol, NE sand sheet, fall 1991	Cahill et al., 1994	700	N.D.	N.D.	300	1300	700
Aerosol, high mass non-storm (fall)	Reid et al., 1994	—	N.D.	N.D.	600	2100	2100
Aerosols, fall storm period	Reid et al., 1994	700	N.D.	N.D.	300	1300	700
Aerosols, spring storm period	Reid et al., 1994	—	N.D.	N.D.	—	—	100
Near-surface lake sediment from cores	Bischoff et al., 1993, 1997	N.D.	300–1000	>1000 ^a	15–30	1400	N.D.
Surface lake sediment from T62	This study	14–19	966–1020	N.D.	N.D.	312–344	179–193
Owens Lake-marginal sediments	This study	19–35	392–646	N.D.	N.D.	418–998	119–138
Alluvial deposits in Owens Valley	This study	4–25	496–954	N.D.	N.D.	258–540	84–202
<50 μ m dust from T62 on lake bed (average)	This study	40 ^b	1250	610	180	960	N.R.
<50 μ m dust from elsewhere in Owens Valley (average)	This study	45 ^b	3750	550	360	390	N.R.

^a Estimated from figure 7 of Bischoff et al. (1997); content of clay fraction only.

^b Includes estimated amount of As in soluble-salt fraction, not analyzed for most samples (see Appendix 1).

and Sr may be mainly derived from the lake bed, whereas As and Sb are mainly derived from alluvial or other sources (though sediment from these sources may be proximal to and even incorporated within the lake-bed sediment). Dust at site T62 is strongly enriched in Ca and Sr relative to the adjacent lake-bed sediments we sampled, implying that Ca and Sr are partly derived from another source or from a different area of the lake bed.

Many studies of dust composition from Owens (dry) Lake have been conducted over the past 20 yr. Data from these studies provide useful comparisons, although they do not include analyses of many of the elements reported here (Table 2). For example, dust aerosols originating from the northern part of the lake bed contain more As than those from the southern part, and dusts collected during the fall (a season much less prone to large dust storms) contain more As, Pb, and Zn than those during the spring (Cahill et al., 1994; Reid et al., 1994). Samples from site T62 contain more As as well as Ba in summer and fall than during winter and spring (Reheis et al., 1999), whereas Ca and Sr are higher in winter and spring. Contents of As, Pb, and Sr measured in dust samples from this study are similar to those from previous studies (Table 2).

Analyses of lake-bed sediment and resuspended alluvium from previous work (Table 2) provide clues to the sediment sources of the dusts. Sr and Ca, for example, must mainly come from lake sediment; Sr is as much as 1400 ppm in near-surface lake sediments of a core taken north of T62 (Bischoff et al., 1993). Ba is somewhat higher in our samples of the Owens lake bed than of the Sierra Nevada alluvium. Ba and additional Sr could be derived from feldspars that characterize the granitic rocks in parts of the Sierra Nevada (Hinkley, 1974). Contents of As are < 35 ppm in our playa and sediment samples but are much greater in other parts of the lake bed; Kusko and Cahill (1984) reported a mean lake-bed As content of 50 ppm, and local As concentrations in the northern and eastern part of the lake bed exceed 150 ppm (E. Hardebeck cited in Reid et al., 1994). Reid et al. (1994) proposed that As could act as a tracer element for the north end of the lake bed. Mine wastes could be an additional source of As (discussed below). The contents of Li and Mg are strongly correlated in the soluble fraction of Owens Valley dust (J. Bischoff, pers. comm.), and in a long

core obtained from Owens (dry) Lake, Li covaries exactly with Mg contained in authigenic clay formed in low-lake conditions (Bischoff et al., 1997). Thus Li in Owens dust is probably derived mainly from the lake bed. This conclusion is supported by high values of Li in the shallow groundwater beneath the lake bed (Table 2; Levy et al., 1999), in lake-marginal springs (2.7–4.2 mg/L), and in Owens Lake water sampled in 1905 before the lake desiccated (57 mg/L; Bradbury and Forester, in press).

4.2.2. Mine waste as a dust source

Owens aerosols from previous studies have Zn contents as high as 2100 ppm (Table 2), which is in general agreement with elevated Zn in our dusts. Elevated Zn and Pb contents were found in dust samples obtained by resuspension of alluvial sediment near Keeler on the northeast side of Owens (dry) Lake (Barone et al., 1979). This association suggests a specific source for Pb, Zn, and possibly other elements in the Owens dust samples, namely, mining and milling wastes from the Cerro Gordo mining district located on the east side of Owens Lake in the Inyo Range. Silver and lead were most actively mined from 1869 to 1876. Zinc-carbonate ores were mined from the same mineralized zone mainly from 1911 to 1919; during these years “Cerro Gordo was a major source of the highest grade zinc carbonate ores produced in this country,” according to Merriam (1963). Zinc-carbonates are almost as soluble as calcium carbonate. The silver-lead-zinc ores also included hydrous arsenates and antimonates of lead; thus, As, Pb, and Sb are likely byproducts of the mining and milling operations. Keeler was the center of the smelting operations as well as the terminus for shipping by barge and steamer across Owens Lake and by wagon and a narrow-gauge railroad. Milling wastes and alluvial sediment in washes draining the mining and processing areas and deposited on the playa margin are likely sources of As, Pb, Sb, and Zn in dust. Supporting this possibility are measurements of aerosols in Owens Valley showing that Pb concentrations increase greatly around Keeler during dust storms (Barone et al., 1981). Also, Pb concentrations in the acid-soluble fraction of sediments in a lake core increased from < 1 ppm to 9 ppm near the lake-bed surface in

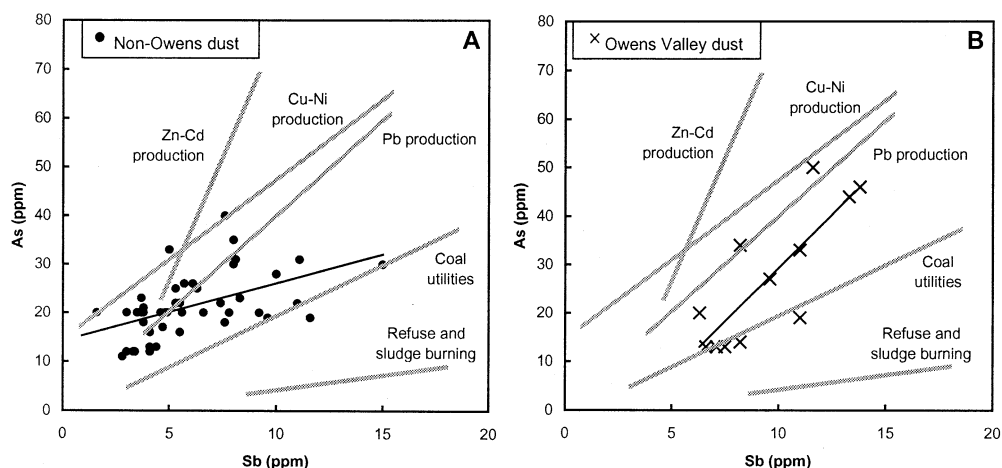


Fig. 10. A comparison of As and Sb concentrations in (A) Owens Valley dust samples and (B) all other dust samples with emission values of these elements from different anthropogenic sources (data of Nriagu and Pacyna, 1988). Gray lines connect maximum and minimum emission values; black lines are linear regressions on dust samples. Emission values were scaled to the figure by dividing each pair of emission figures by 10 or 100 as appropriate.

deposits that just predate the 1872 Owens Valley earthquake (Smoot et al., 2000). As the core was obtained from a site ~15 km southwest of Keeler, these data strongly suggest that mining-derived Pb is widely distributed over the lake bed.

To test the hypothesis that mining and milling wastes from the Cerro Gordo mining district are contributing to modern dust in Owens Valley and the region as a whole, we compared the composition of modern dust samples to the proportions of As and Sb reported as atmospheric emissions from different anthropogenic sources using data of Nriagu and Pacyna (1988). The ratio of As and Sb in emissions is assumed to be distinct for each type of emission source, so a plot of minimum and maximum emission rates for a source yields a trend line that is believed to be characteristic of the source (Fig. 10). A mixing trend of ratios of non-Owens dust is most similar to that for Pb mining and production; some subgroups of samples are similar to emissions produced from coal-burning power plants and possibly from Zn-Cd production. Notably, the average composition of Owens Valley dusts is clearly similar to emissions

from Pb mining. These relations lend support to a mining source as a contributor to Owens and regional dusts. The only possible nearby source of coal-fired emissions is a salt-processing plant at Searles Lake, California, 80 km southeast of Owens (dry) Lake; there are no coal-fired power plants in California, and the nearest is ~400 km to the southeast in Arizona. In addition, concentrations of Sb in aerosols around the Los Angeles area are below the detection limit ($< 1 \text{ ng/m}^3$; Glen Cass, pers. comm.), suggesting this major population center is not a principal source of Sb in the study area. Emission rates of As and Pb can potentially account for regional dust-deposition rates of these metals but not for the higher rates in Owens Valley (Table 3).

4.2.3. Transport of Owens Valley dust

The systematic decreases of As, Ba, and Sb contents with distance away from Owens (dry) Lake (Fig. 8) suggest that significant quantities of dust from southern Owens Valley are

Table 3. Comparison of element deposition (flux) and emission rates (g/ha/yr) [N.R., not reported]

Element	Regional (this study)	Owens (this study)	Remote ^a	Rural ^a	Urban ^a	Greenland ^b	Los Angeles ^c (emissions)	Global volcanic ^d (emissions)
As	0.39–3.6	1.8–42	0.31	10–20	25–60	N.R.	2–3	(0.0027) ^e
Cd	0.0082–1.2	0.044–1.1	0.0023–0.050	1.2–8.8	7.0–260	0.0099	N.R.	0.0053
Cr	1.6–17	2.8–71	3.0	10–360	10,600	N.R.	25–30	N.R.
Cu	5–90	52–370	0.012–1.9	18–230	160–600	N.R.	N.R.	0.020
Mn	18–160	59–800	6.2	21–250	<1,000	N.R.	N.R.	N.R.
Mo	0.096–0.67	0.25–3.6	N.R.	<10	N.R.	N.R.	N.R.	N.R.
Ni	1.0–13	2.9–65	N.R.	10–<230	100–<2,240	N.R.	8–12	N.R.
Pb	2.5–75	32–500	0.012–9.3	19–320	100–12,360	0.099	90–95	0.0168
Sb	0.12–1.1	0.56–24	0.16	<10	N.R.	N.R.	N.R.	(0.0001)
V	2.6–22	7.0–110	N.R.	36–12,400	43–8,300	N.R.	N.R.	N.R.

^a Sources in Galloway et al. (1982; bulk samples only).

^b From Figure 2 of Sherrell et al. (2000).

^c Estimated from Table 4.2 in South Coast Air Quality Management District (2000).

^d Calculated from data in Table 3 of Hinkley et al. (1999).

^e Values in parentheses from Kilauea only (data of Hinkley et al., 1999).

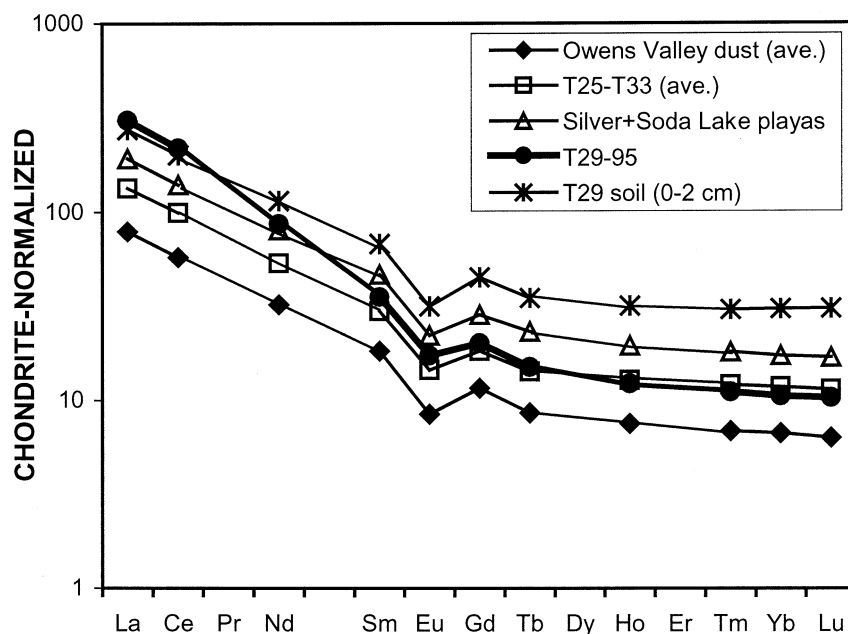


Fig. 11. Rare-earth element contents of selected dust and sediment samples. Note relative enrichment of light rare earths in dust sample T29-95.

being transported at least 400 km to the east. Increases in abundance of As, Ba, and Sb in dust samples taken away from the lake bed within Owens Valley suggest either (1) preferential concentration of finer-grained or lighter particles bearing these elements as dust plumes migrate away from Owens Lake or (2) additions of these elements from alluvial sources (such as reworked tailings) in Owens Valley. Seasonal variations in dust storm activity on Owens (dry) Lake, combined with flooding events that exposed fresh sediment from the mining areas near Keeler to wind erosion, may help explain the large annual variations in concentrations and fluxes of these elements in Owens Valley and elsewhere (Fig. 3B). Changes in dominant wind direction probably also influence the transport of dust out of Owens Valley. Examination of unpublished data from the Geomet station at site T62 (Breed, 1999) shows that strong winds blew more frequently from the south during 1995, whereas strong northerly winds dominated during 1996.

The old dust from the Amargosa area (Yucca Mountain) is generally much closer in composition to the alluvial and playa sources than to the modern dust in several key elements: As, Ba, Cr, Ni, and Sb (Figs. 3C, 4). The old dust ought to reflect the prehuman-impact dustfall in the region (Reheis et al., 1997). Both Owens Valley and anthropogenic emissions may contribute As, Cr, Ni, and Sb, but Ba is chiefly derived from crustal sources (Church et al., 1990), and its enrichment, as well as that of As and Sb, by implication, in modern Amargosa dust is most likely due to transport of dust from Owens Valley.

4.2.4. REE source

Samples from dust traps T23 (one) and T29 (two) are the only dust samples that show significant enrichment in some rare-earth elements; these samples contain two to three times as much La and more Ce and Nd than other dust samples (Reheis

et al., 1999). They are also enriched in light rare earths relative to sediments from the nearest playas, Silver and Soda Lakes (Figs. 1, 11), and to the surface sediment at sites T23 and T29. Interestingly, these two sites are also the closest to the Mountain Pass rare-earth mine located midway between them. The rare earths are mined from a carbonatite body that is enriched in Ba, Sr, and Pb; all of these elements are also elevated in alluvial sediments derived from natural erosion of the carbonatite (J. R. Knott, pers. comm.). Sites T23 and T29 are also higher in Ba than dusts from other Mojave sites but not in Sr and Pb (Reheis et al., 1999). The on-site processing discharges water containing significant amounts of rare earths that are fractionated by the processing, yielding a strong negative Ce anomaly in scale left when the water evaporates (J. R. Knott, pers. comm.). The dust samples from nearby sites do not show this negative anomaly (Fig. 11). If this mining area is the source of the higher amounts of light rare earths in the dusts, then this enrichment must originate either from the actual mining and blasting or from the associated alluvial sediment. Dust samples that accumulated before the opening of the mine would be needed to resolve this issue.

4.3. Comparison to Global Dust Enrichments

Many studies have reported ubiquitous enrichment of As, Cd, Cr, Cu, Mo, Ni, Pb, Sb, Sn, V, and Zn in atmospheric dusts (e.g., Galloway et al., 1982; Church et al., 1990; Hinkley et al., 1999a). Of these elements, As, Cd, Cu, Mo, Pb, Sb, and Zn are thought to be dominantly contributed by anthropogenic emissions worldwide (mobilization factors, i.e., emissions from human sources divided by emissions from natural sources > 10); the others, Cr, Ni, Sn, and V, reflect a majority of anthropogenic emissions mixed with natural sources, including soil dust and volcanic emissions (mobilization factors of 2–10). A

comparison of enrichment factors (Fig. 9B) shows that dusts in southern Nevada and California are less enriched in many trace metals than are dusts in the North Atlantic Ocean sampled near Bermuda (commonly affected by industrial emissions from the United States) and at the South Pole (Duce et al., 1975). The overall pattern and relative amounts of enrichment of trace elements in this study are very similar to those reported for dust samples in snowpack from the Mogollon Rim in central Arizona (Barbaris and Betterton, 1996) due east of our study area and for dust collected from snowpack and by dry deposition on airfoil devices from several high- and low-altitude sites across the southwestern United States (Hinkley et al., 1999a). These studies by several investigators in the southwestern United States show that different sampling methods achieve similar results and impart robustness to our interpretation of dust source areas.

Deposition rates of potentially toxic metals are perhaps more relevant to environmental studies than relative enrichment values. We compared element fluxes (kg/ha/yr; Table 3) in the study area to bulk atmospheric fluxes in remote (Greenland and Antarctica), rural, and urban areas (Galloway et al., 1982; Sherrell et al., 2000; Matsumoto and Hinkley, 2001). Fluxes of Cd, Cr, Mn, and V are similar to or somewhat larger in Owens Valley than at the regional dust-trap sites; these fluxes are similar to or lower than those reported for other rural areas and in some cases are comparable to those in Greenland and Antarctica. The flux of Ni is significantly higher in Owens Valley than at the regional sites, despite no difference in enrichment values (Figs. 3A, 9A). The larger overall dust flux in Owens Valley probably results in a larger deposition rate of Ni there. Fluxes of As, Pb, and Sb are an order of magnitude larger in Owens Valley than at the regional sites and are similar to or greater than rates reported for other rural areas. Fluxes of As and probably Sb in Owens Valley are actually as high as urban-deposition rates. These results are significant, because the dust traps used in this study were originally designed to provide a comparison to the rate of dust additions to soils (Reheis et al., 1995).

It is difficult to apportion the contributions of distant (urban pollution, volcanic gases) vs. local (soil dust) sources to the composition of dust samples in this study. Reynolds et al. (in press) interpret data from snow samples collected at high altitudes in the southwestern United States to indicate that snow with low concentrations of dust has larger enrichment factors for trace metals and represents far-transported material that is a combination of modern industrial fallout and volcanic emissions, whereas snow with high concentrations of dust is less enriched and represents more directly transported local or regional dust. However, the dust samples in the present study were nearly all collected at low altitudes and represent an average composition of dust deposited over several months to 2 yr. An air-filtration study found that crustal enrichment factors for Cd, Co, Cr, Cu, Ni, and Zn in Tucson, Arizona, were significantly lower than those in a nearby rural area and suggested that these non-soil species might be contributed by nonurban sources such as smelters, power plants, and unspecified natural sources (Moyers et al., 1977). The large urban areas of coastal California and smelters in Mexico are west of and generally upwind of many of the study sites (Fig. 1). However, recent data indicate that although emission rates of

As, Cr, Ni, and Pb from the Los Angeles area may account for a portion of these metals deposited in regional dust, they cannot account for the high deposition rates in the Owens Valley area (Table 3; South Coast Air Quality Management District, 2000).

We suggest that high deposition rates of As, Pb, and Sb in Owens Valley reflect local-source sediment with anomalous geochemical compositions. By implication, the dusts in the region, e.g., snowpack samples from the Mogollon Rim (Fig. 9B) and possibly aerosols in southwestern national parks, also may be influenced by these components from Owens, especially during the late winter and spring, e.g., see back trajectories of dust-laden air masses arriving in Grand Canyon National Park (Vasconcelos et al., 1996). The non-salt fraction of dust from the area around Owens (dry) Lake consists of 50 to 90% of particles in the $< 10\text{-}\mu\text{m}$ size range (Reheis, 1997); dust of this size can be transported more than 1000 km even by light storms (e.g., Tsoar and Pye, 1987). The ready solubility of the salt component of Owens dust suggests that the salt and associated trace metals can be leached rapidly into soils after settling out.

Regional flux rates of Cd, Cr, and possibly Mo, Ni, and V are similar to those measured in remote areas elsewhere (Table 3); in Owens Valley, these rates are either low or slightly elevated due to the high dust fluxes. If we assume that these fluxes represent a background, far-traveled measure of human and volcanic emissions, then we can estimate the proportion of regional fluxes of other metals that might be contributed by Owens Valley. For example, the flux of As in the study area outside of Owens Valley is as much as 10 times greater than that in other remote areas, and the mean As flux (not shown) is five times greater. Thus, as much as 80 to 90% of As deposited in the study region might be coming from Owens Valley. Similar contributions are estimated for Pb and Sb. Hence, so-called soil-dust sources may locally and regionally contribute a significant proportion of metals in dust that has been previously attributed to anthropogenic and volcanic emissions.

5. CONCLUSIONS

Samples of deposited dust from many rural sites in southern Nevada and California are enriched in As, Ba, Cr, Ni, and Sb relative to sediment samples of presumed local sources such as dry playas and alluvium. In general, these dusts are somewhat less enriched in many trace metals relative to average crustal composition than are dusts in the North Atlantic Ocean and at the South Pole (Duce et al., 1975) but are quite similar to dusts from elsewhere in the southwestern United States (Hinkley et al., 1999a). Dusts in our study are depleted relative to the sampled sources in elements usually found in heavy minerals, such as Zr, Hf, Sc, and certain rare earths, probably due to winnowing by transport. The only dust samples enriched in some rare-earth elements are from sites near natural sediments derived from a carbonatite body. The composition of modern dust sampled at site T62 on the bed of Owens (dry) Lake is distinctively enriched in As, Li, Mg, Sb, and Sr relative to regional dust samples.

The compositions of dust samples in the study area reflect four principal dust sources: (1) alluvial sediments (Rb and K, rare earths, and perhaps Th), (2) carbonate-rich dust from playas (Sr, Ca, and perhaps U), (3) Owens Valley (As, Ba, Li, Pb, and Sb), and (4) anthropogenic and/or volcanic emissions

(Cr, Ni, and additional As and Sb). Alluvium derived from lithologic types, such as metasedimentary rocks, also contributes Cr and Ni to dust. A comparison of dust and source samples in Owens Valley with previous analyses of dust, lake bed sediment, resuspended sediment, and anthropogenic emission sources shows that Owens (dry) Lake and adjacent and incorporated mining wastes from the Cerro Gordo mining district are the primary sources of As, Li, Pb, Sb, and Sr in Owens Valley dusts.

Systematic decreases in concentrations of As, Ba, and Sb in dust with distance away from Owens (dry) Lake suggest that significant quantities of dust are being transported at least 400 km to the east. Old dust from Yucca Mountain is distinctly lower in As, Ba, and Sb abundances relative to modern dust from the Amargosa region; thus, Owens Valley was apparently not an important source of the old dust. We conclude that high deposition rates of As, Pb, and Sb in Owens Valley reflect local-source sediment of anomalous composition, and by implication, the dusts in the region (e.g., snowpack samples in the southwestern United States and possibly aerosols in southwestern national parks) may also contain Owens Valley components.

This study shows the important role that some soil-dust sources play as geochemical "hot spots" that locally and regionally contribute a significant proportion of metals in dusts previously attributed to anthropogenic emissions and to lesser amounts of volcanic emissions. These conclusions could be greatly refined by isotopic analyses of Sr and Pb relative to sediments in Owens Valley and other potential sources. Studies should be initiated on the effects on soils, plants, and animals by the incorporation of dust rich in toxic metals, especially in areas close to Owens Valley. Fluorine concentrations in dusts should also be examined, because F is strongly correlated with As in shallow ground water around Owens (dry) Lake (Levy et al., 1999).

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Appendix 1. Comparison of selected elements between processed (salts and organics removed), unprocessed, and soluble-fraction samples. [1999 samples not affected by Zn from galvanized screens. Fe, Ca, Na, K, and Mg in percent; all others, listed in alphabetical order, in ppm].

Sample number	Method	Fe	Ca	Na	K	Mg	As	Ba	Ca	Co	Cr	Cs	Cu	Eu	La	Li	Mo	Ni	P	Pb	Rb	Sb	Sc	Sr	U	Zn
T10-95 proc.	INAA	4.1	2.1	2.6	1.6		33	755	72	11.0	140	8.6		0.88	38						140	5.0	12.0	290	3.2	329
T10-97 proc.	ICP	3.6	1.7	2.7	1.9	1.5	20	2200	70	15.0	62	6.3	160	37	56	1.9	42			100	130	3.8	12.0	360	2.6	320
T10-99 unproc.	INAA*	1.2	7.1	3.2	4.1	1.0	11	325	28	7.1	21	2.4	150	0.43	15	22	2.6	66	1060	130	42	1.8	3.7	700	1.3	86500
T15-91 proc. +	INAA	3.3	3.8	2.6	2.5	2.1	40	724	87	12.0	49	7.5	200	1.10	44	86	2.4	42	2	180	120	7.7	9.9	360	3.7	18300
T15-97 proc.	ICP	3.7	1.3	2.8	1.5	1.6	20	780	68	13.0	63	9.3	170	37	78	2.4	39			38	150	7.8	12.0	290	3.1	570
T15-99 unproc.	INAA*	1.8	7.6	4.6	4.4	1.1	19	444	44	7.6	31	4.6	59	0.62	23	46	3.8	46	2400	88	74	4.0	5.5	580	2.3	49500
T16-91 proc.	ICP	2.5	9.4	1.8	2.4	3.4	20	610	120	11.0	48	5.2	420		61	44	2.3	32		230	92	4.6	8.0	350	2.9	19000
T16-99 unproc.	INAA*	1.9	11.0	2.8	3.0	2.1	12	461	62	8.4	61	3.7	62	0.68	34	25	1.8	72	1200	84	64	3.5	5.6	535	2.4	24000
T37-91 proc.	INAA	3.4	1.8	2.2	2.7	2.1	31	719	73	19.0	52	17.4	430	1.00	36	170	3.2	72	2	240	143	11.1	11.0	297	4.5	55300
T37-99 unproc.	INAA*	2.5	6.6	3.6	4.6	1.3	21	623	51	11.0	45	10.1	85	0.72	25	111	3.2	57	2700	192	112	7.4	7.4	677	5.1	37800
T62-0592 proc.	INAA*	2.4	8.0	2.0	2.3	5.1	19	1120	40	10.0	20	10.5	290	0.52	22	830	0.6	31	2	140	106	11.0	6.3	1070	2.9	30000
T62-0592 unproc.	INAA*	1.7	5.3	1.7	10.6	2.7	18	915	29	7.5	16	7.8	36	0.41	16	468	6.0	33	450	115	80	8.5	4.7	846	2.9	19000
T62-0593 proc.	INAA*	2.6	7.9	2.1	2.4	5.0	13	1390	43	11.0	21	11.4	240	0.57	25	790	0.5	19	2	55	118	7.5	7.0	1220	3.0	4820
T62-0593 unproc.	INAA*	1.9	5.6	1.7	11.5	2.8	16	1150	32	7.5	15	8.2	29	0.42	18	415	2.4	28	430	39	86	7.0	5.1	926	2.9	3070
T62-0595 proc.	INAA	2.8	7.3	2.9	3.6		14	1180	48	13.0	25	12.0		0.68	27			23			136	8.2	7.8	1070	3.4	4080
T62-0595 unproc.	INAA*	2.4	5.1	2.1	9.2	2.6	17	1054	38	11.0	21	10.5	42	0.54	22	414	4.7	14	540	65	116	6.6	6.8	843	3.4	3240
T62-0595 salt only	INAA*	0.0	0.6	#	35.0	0.0	37	26	0	0.1	2	0.0	9	0.01	0	3	18.0	2	92	0	1	2.0	0.0	22	4.8	17
T62-1095 proc.	INAA	1.9	5.7	2.2	13.0		34	532	29	8.6	17	8.2		0.39	16			17			87	8.2	5.0	774	5.9	4250
T62-1095 salt only	INAA*	0.0	0.7	#	33.0	0.0	72	45	1	1.0	3	0.1	9	0.02	0	37	35.0	7	380	1	3	6.6	0.1	49	9.1	64
T-62-0599 unproc.	INAA*	2.2	4.4	2.0	14.0	2.3	30	560	31	9.2	21	9.4	36	0.47	17	305	13.0	13	570	44	110	6.0	5.9	600	6.6	245

* Mg, Cu, Li, P, and Pb analyzed by ICP-MS and ICP-AES.

+ Represents average of two replicate analyses.

Detection limit exceeded by amount of element present.

Appendix 2. Comparison of ratios of selected elements in dust samples to those of nearby source-sediment samples. [Dust data are individual samples except where specified (data in Reheis et al., 1999); source sediment data, from Table 1, are averages of closest samples to individual dust traps.]

Samples	Fe	Ca	Na	K	As	Ba	Ce	Co	Cr	Cs	La	Nd	Ni	Rb	Sb	Sc	Sr	Ta	Th	U	Zr
Mixed alluvium, Amargosa area ($n = 4$)																					
T13-91	0.67	0.29	1.4	0.96	1.3	1.0	0.85	1.1	0.87	0.71	0.85	0.87	0.63	0.86	1.8	0.85	0.74	0.86	0.81	1.0	0.68
T14-91	0.76	0.37	1.4	0.68	1.5	1.1	0.87	1.2	0.97	0.68	0.89	0.87	1.4	0.83	2.0	0.93	0.79	0.84	0.77	0.99	0.52
Metasedimentary alluvium, Amargosa area ($n = 4$)																					
T11-91	0.75	0.28	1.4	0.62	2.6	1.0	0.82	1.4	0.88	1.1	0.76	0.81	1.6	0.91	4.1	0.87	0.67	0.81	0.74	1.1	0.51
T11-95	0.77	0.24	0.73	0.79	1.9	1.0	0.84	0.59	1.7	1.0	0.82	0.81	1.0	1.1	3.2	0.97	0.79	1.1	0.87	1.1	0.79
Limestone alluvium, Amargosa area ($n = 3$)																					
T15-91	0.73	1.3	0.90	0.73	2.3	1.1	0.79	1.2	1.0	0.90	0.81	0.83	2.1	0.76	3.1	0.97	1.3	0.67	0.68	0.80	0.45
T15-97	0.85	0.45	0.56	0.85	1.2	1.2	0.65	1.3	1.3	1.1	0.70	0.58	2.0	1.0	3.2	1.2	1.0	0.53	0.54	0.70	
"Peter's" playa, Amargosa area ($n = 2$)																					
T10-95	1.3	0.16	0.70	0.79	3.1	0.80	0.89	1.5	3.6	2.0	0.92	0.77	3.4	1.4	6.0	1.4	0.30	1.3	0.90	0.65	0.66
T10-97	1.2	0.13	0.83	0.82	1.9	2.3	0.87	2.0	1.6	1.4	0.89	0.74	1.9	1.3	4.6	1.4	0.37	0.73	0.93	0.52	
Sarcobatus Flat, Amargosa area ($n = 2$)																					
T35-95	0.91	0.19	0.81	0.73	1.9	1.2	0.76	1.4	3.6	1.0	0.84	0.73	3.3	0.96	7.0	1.1	0.92	0.50	0.75	0.71	
T36-95	1.0	0.26	0.86	0.75	1.9	1.2	0.67	1.0	3.0	1.3	0.74	0.68	3.6	0.96	4.7	1.2	0.99	0.92	0.64	0.83	3.1
Death Valley, Amargosa area ($n = 3$)																					
T39-91	0.94	1.5	1.5	0.99	1.8	1.1	0.77	0.79	1.3	1.1	0.78	0.71	0.99	0.97	3.9	0.89	0.90	0.36	0.69	0.60	
Danby Lake, Mojave ($n = 4$)																					
T25-91	0.63	1.1	0.69	0.74	2.9	1.0	0.88	0.82	1.1	1.0	0.85	0.81	1.6	0.83	5.3	0.80	0.71	0.44	0.74	0.56	
T25-95	0.78	0.32	0.39	0.91	1.7	1.1	0.75	0.99	4.6	1.4	0.76	0.67	7.4	1.1	4.1	0.92	0.74	1.1	0.72	0.62	0.76
T25-97	0.63	1.3	0.36	0.81	1.3	1.2	0.92	0.75	1.2	1.2	0.89	0.87	1.5	1.0	2.2	0.80	0.85	0.50	0.81	0.62	
Bristol Lake, Mojave ($n = 4$)																					
T27-93	0.63	0.45	1.0	0.69	1.7	1.3	0.89	0.98	1.1	0.90	0.86	0.85	1.8	0.81	3.8	0.85	0.54	0.54	0.73	0.80	
T27-95	0.75	0.42	0.75	0.93	1.0	1.6	0.76	0.90	2.6	1.1	0.76	0.67	4.7	0.97	2.7	0.91	0.68	1.2	0.62	0.78	0.75
T27-97	0.66	0.70	0.52	0.79	0.84	1.5	0.89	0.91	1.2	1.0	0.89	0.87	1.8	0.88	2.2	0.85	0.70	0.56	0.78	0.94	
Silver + Soda Lakes ($n = 4$)																					
T29-95	0.85	0.24	0.56	0.92	1.3	1.3	1.6	0.97	2.7	1.7	1.6	1.1	3.8	1.3	3.4	1.0	0.39	1.0	0.62	0.55	0.57
T29-97	0.78	0.27	0.63	1.0	1.1	1.8	1.4	1.3	1.5	1.7	1.6	0.94	1.8	1.4	3.2	1.0	0.47	0.68	0.60	0.46	
Silver Lake ($n = 2$)																					
T30-91	0.60	0.49	1.3	0.81	1.5	1.2	0.80	0.98	1.2	1.0	0.78	0.84	2.0	0.98	3.0	0.91	0.65	1.0	0.56	0.66	0.82
T30-93	0.55	0.41	1.6	0.81	1.7	1.2	0.84	1.9	1.4	0.88	0.81	0.84	2.8	1.0	3.0	0.84	0.65	0.51	0.53	0.63	0.0
T30-97	0.55	0.52	0.78	0.85	0.81	1.4	0.84	0.62	1.4	0.98	0.83	0.89	1.4	1.1	0.72	0.70	0.94	0.25	0.61	0.72	0.0
Owens (dry) Lake ($n = 2$)																					
T62 winter ($n = 4$)	0.54	2.6	1.0	0.63	0.89	1.2	0.86	0.57	0.64	0.63	0.83	0.80	0.84	0.52	2.4	0.59	3.5	0.65	0.76	0.75	0.93
T62 summer ($n = 3$)	0.55	1.9	2.0	0.67	1.6	1.4	0.87	0.57	0.86	0.59	0.80	0.78	1.00	0.51	2.4	0.59	2.2	0.60	0.69	1.4	0.81
Alluvium, Owens Lake margin ($n = 3$)																					
T62 winter ($n = 4$)	0.55	1.3	1.6	1.2	0.60	2.1	0.51	0.56	0.32	0.94	0.54	0.49	0.48	1.1	1.8	0.50	1.8	0.50	0.62	0.55	0.21
T62 summer ($n = 3$)	0.57	0.94	3.3	1.2	1.1	2.5	0.52	0.56	0.44	0.88	0.51	0.47	0.57	1.1	1.8	0.50	1.1	0.45	0.56	1.1	0.18
Mixed alluvium, Owens River valley ($n = 2$)																					
T63-0592 winter	0.32	2.1	1.3	0.53	3.1	3.2	0.27	0.77	0.46	1.1	0.27	0.24	2.6	0.52	5.2	0.28	2.1	0.28	0.44	0.68	0.09
Volcanic alluvium, Coso Range, Owens Valley ($n = 2$)																					
T64-0592	0.41	0.96	2.6	0.50	2.2	1.7	0.42	0.62	0.71	0.68	0.40	0.46	1.5	0.45	5.9	0.35	0.74	0.52	0.45	0.19	0.61
T64-0596	0.51	0.91	0.93	0.77	0.96	8.7	0.64	0.41	1.0	0.87	0.57	0.57	1.3	0.69	2.7	0.39	1.4	0.18	0.52	0.74	
Inyo Range + volcanic alluvium, Owens Valley area ($n = 2$)																					
T67-0594	1.0	0.23	2.5	1.0	2.2	5.1	0.77	1.3	1.0	1.4	0.74	0.83	1.7	0.93	8.7	0.91	0.95	0.81	0.97	1.5	0.58
Means of dust/proximal source ratios																					
Dust/alluv. source	0.8	0.4	1.3	0.8	1.8	1.6	0.8	1.2	1.1	1.0	0.8	0.8	1.5	0.9	3.7	1.0	0.9	0.8	0.8	1.0	0.5
Dust/playa source	0.8	0.6	0.8	0.8	1.6	1.3	0.9	1.1	2.0	1.2	0.9	0.8	2.7	1.1	3.7	1.0	0.7	0.7	0.7	0.7	0.2